Modelling Traffic on Motorways:

State-of-the-Art, Numerical Data Analysis, and Dynamic Traffic Assignment

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Outline

- **Outline**
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  - Cellular Automata Models of Road Traffic
- **Part II: Numerical Analysis of Traffic Data**
  - Assessing Data Quality
  - Off-Line Travel Time Estimation
  - Tempo-Spatial Congestion Maps
- **Part III: Integrated Dynamic Traffic Assignment**
  - Combining Departure Time and Route Choice
  - Efficient Dynamic Network Loading
- **Conclusions and Perspectives**

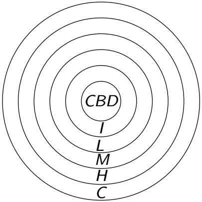
Part I

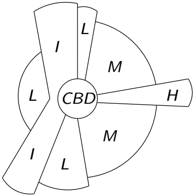
State-of-the-Art

Land-Use and Socio-Economic Behaviour

The demand for transportation is induced by people wishing to participate in spatially separated social, cultural, economic, . . . activities.

⇒ Land-use models (Burgess 1925, Hoyt 1939, . . .)





CBD	=	central business district
I	=	industry zone
L/M/H	=	low-, middle-, and high-class residents
C	=	commuter zone

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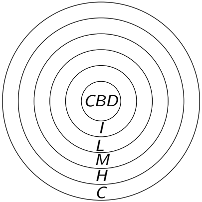

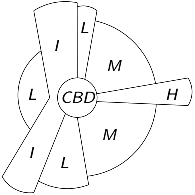

$\Rightarrow$

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Geosimulation 2000 (sprawl)

SISTA

Trip-Based Transportation Planning Models

Classical approach, e.g., the four-step model (4SM).
Travellers make certain decisions, thereby undertaking trips.

- Trip generation ⇒ *How many trips ?* ⇒ aggregation
- Trip distribution ⇒ *Where are they going ?* ⇒ OD matrix
- Modal split ⇒ *What mode of transportation ?*
- Traffic assignment ⇒ *Which routes ?*

Trip-Based Transportation Planning Models

Classical approach, e.g., the four-step model (4SM).
Travellers make certain decisions, thereby undertaking trips.

- Trip generation
- Trip distribution
- Modal split
- Traffic assignment

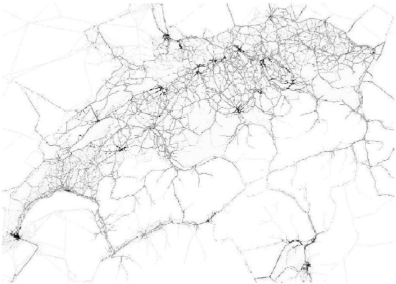
Route choice behaviour as dictated by Wardrop's criteria:

User equilibrium $\leftrightarrow$ System optimum

Activity-Based Transportation Planning Models

Basic units are not trips but household activity patterns.

- Generation of a synthetic population.
- Generation and scheduling of activity patterns $\Rightarrow$ agent plans.
- Physical propagation of agents (plan execution).
  $\Rightarrow$ Day-to-day and within-day dynamics lead to rescheduling.



Multi-agent simulation

$\Downarrow$

"Switzerland at 08:00"

Macroscopic and Mesoscopic Traffic Flow Models

Describe how traffic propagates physically on a road.
Based on partial differential equations (high level of aggregation, low level of detail).

Macroscopic:

Fluid-dynamic models treat traffic as a compressible fluid (Navier-Stokes).

Mesoscopic:

Gas-kinetic models treat traffic as a many-particle system, deriving macroscopic equations from microscopic driver behaviour.

Microscopic and Submicroscopic Traffic Flow Models

Microscopic models explicitly consider interactions beween vehicles in a traffic stream (low level of aggregation, high level of detail).

Car-following submodel

- Stimulus-response.
- Optimal velocity.
- Psycho-physiological spacing.
- Traffic cellular automata.
- Based on queueing theory.

Lane-changing submodel

- Modelling gap acceptance.
- Mandatory versus discretionary lane changes.

Submicroscopic models incorporate physical characteristics such as engine performance, gearbox operations, . . . and human decision taking processes.

Historic Origins of Cellular Automata

Introduced in 1948 by von Neumann and Ulam; evolving in the 70s towards Conway's popular *"Game of Life"*:

- Lattice $\mathcal{L}$.
- States Σ.
- Local neighbourhood $\mathcal{N}$.
- Local transition rule δ.

$\Rightarrow$ Global behaviour arises from local rule-based interactions.

In the 80s, Wolfram provided popularisation through an abundance of empirical experiments.

Cellular Automata Models of Road Traffic

Consider a one-dimensional lattice $\mathcal{L}$ ($\Delta X = 7.5$ m, $\Delta T = 1$ s, $v_{\text{max}} = 5$ cells/time step), corresponding to a single-lane traffic cellular automaton (TCA). Suppose the following rule set applies:

R1: acceleration and braking

$$v_i(t) \leftarrow \min\{v_i(t-1)+1, g_{s_i}(t-1), v_{\text{max}}\}$$

R2: randomisation

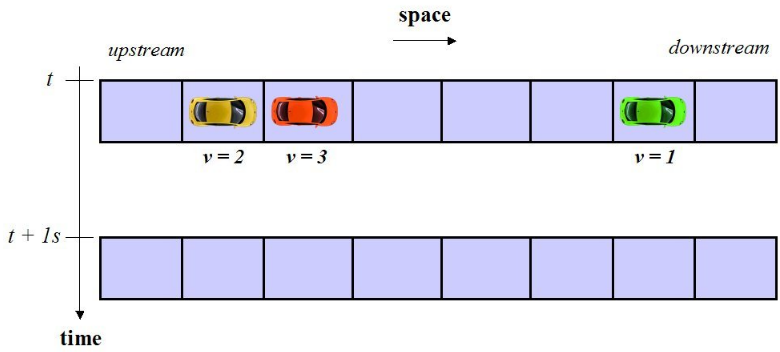
$$\xi(t) < p \Rightarrow v_i(t) \leftarrow \max\{0, v_i(t)-1\}$$

R3: vehicle movement

$$x_i(t) \leftarrow x_i(t-1) + v_i(t)$$

$\Rightarrow$ Apply TCA rules to all vehicles in parallel.

Executing the Rule Set: An Illustrative Example



Set of local rules ⇒ car-following submodel

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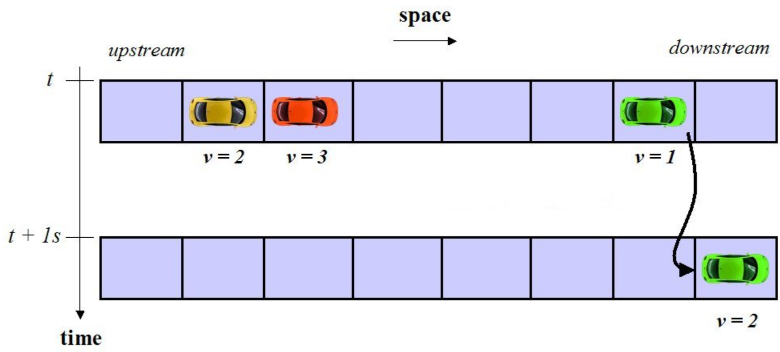

→ The green car can accelerate from 1 to 2 cells/time step.

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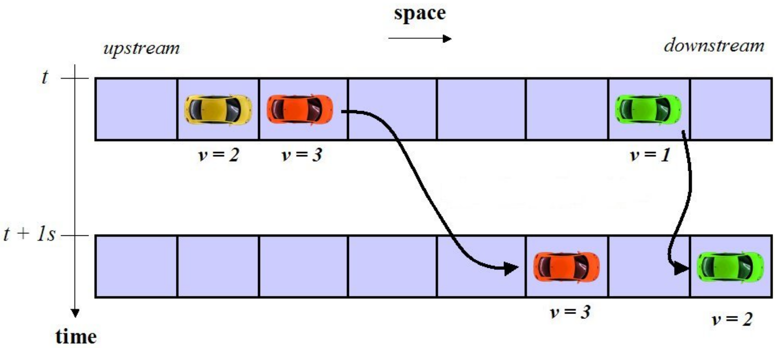
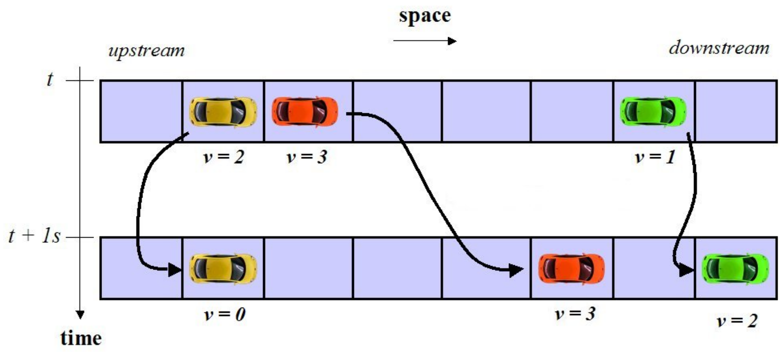


→ The red car maintains its speed.

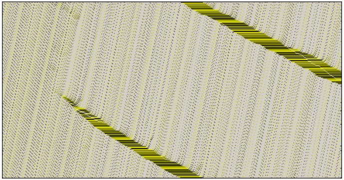
Executing the Rule Set: An Illustrative Example



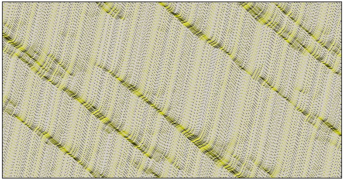
→ The yellow car must brake and stop to avoid a collision.

Some Flavours of Traffic Cellular Automata Models

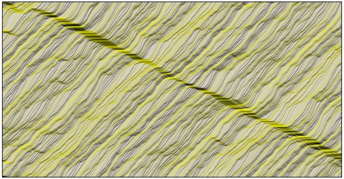
Velocity-dependent randomisation



Stochastic



With brake-lights



⇒ TCA+ Java^{TM} Simulator (http://smtca.dyns.cx)

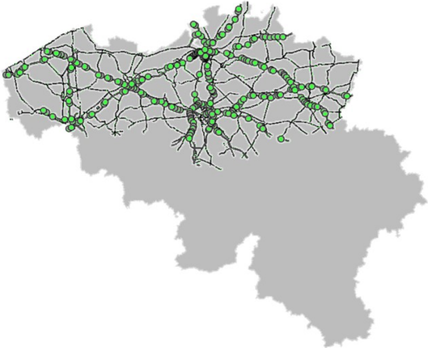
Part II

Numerical Analysis of Traffic Data

Collecting Traffic Flow Measurements

Consider Flanders' motorway road network:

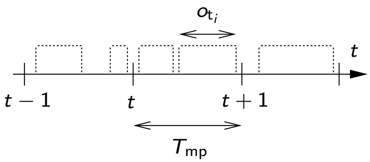
- Some 1600 loop detectors (with approximately 200 cameras).
- On for each lane, right before and after a complex.
- $\approx 10^6$ measurements/year $\approx$ 3.24 GB.

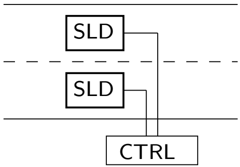


Single Inductive Loop Detectors

Each time a vehicle i passes over the detection zone, it is counted and its on-time o_{t_i} recorded. After a period T_{mp} of one minute, the following measurements are aggregated:

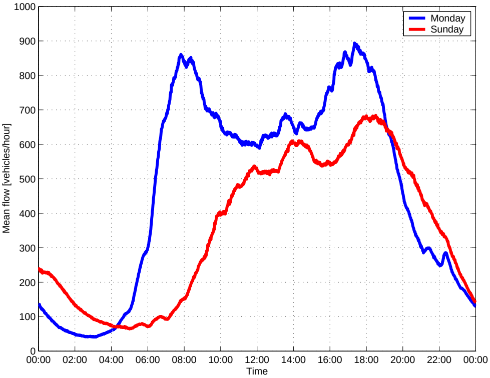
- Number of cars q_c (internal classification !).
- Number of trucks q_t (internal classification !).
- Occupancy ρ.
- Time-mean speed $\overline{v}_t$ (estimated !).





Raw Traffic Flow Measurements

Consider the average flows on all Mondays and Sundays in 2003:

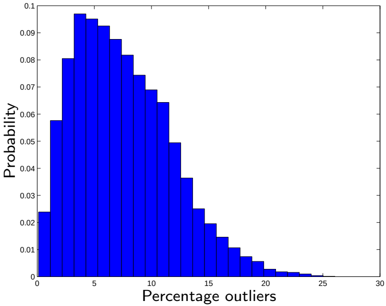


⇒ The Monday morning and evening peaks are clearly visible.

⇒ Sunday has an afternoon peak, increasing in intensity.

Statistical Outlier Detection

As opposed to structural failures of single inductive loop detectors, occasional errors occur as outliers in the data:



Summary statistics for 2003

Maximum	=	24.5 %
Mean	=	7.5 %
Std. dev.	=	4.4 %

$\Rightarrow$ Automatically detect and remove statistical outliers.

$\Rightarrow$ Fill in the missing values (e.g., reference days, multiple imputation, time series analysis, non-parametric models, . . .).

Assessing Detector Malfunctioning

Based on the Daily Statistics Algorithm (DSA) of Chen et al. 2003.
For example, consider the following score for loop detector i:

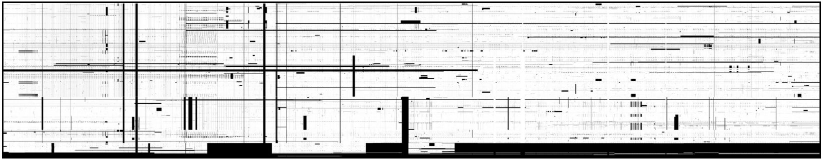
High occupancy samples

$S_2(i, T_{\text{DSA}}) = \#\text{samples during } T_{\text{DSA}} \text{ with } \rho_i > \rho^*$.

- For the year 2001, the database contained 1654 detectors.
- $T_{\text{DSA}} = 60$ minutes.
- $\rho^* = 35$ %.

$\Rightarrow$ Highly detailed detector maps
(e.g., 24 hours $\times$ 365 days = 8760 pixels).

Illustrative Detector Maps



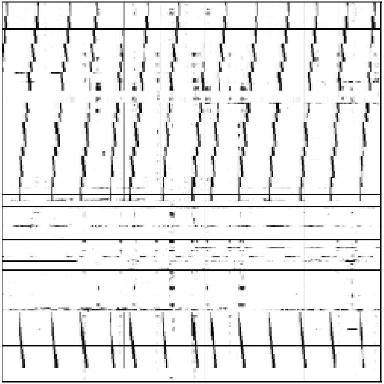
Horizontally: hour-of-year.
Vertically: detector ID.

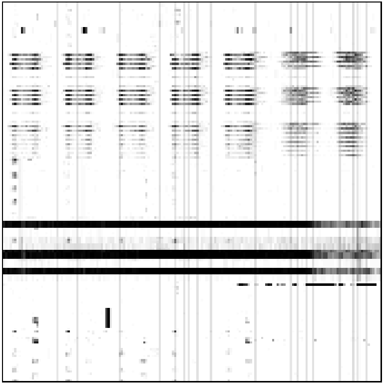
$\Downarrow$

Dark horizontal lines: detector failure during a certain time period.
Dark vertical lines: failure of several neighbouring detectors.
Long vertical lines: archival failure at the central database.

Studying 2001 $\longrightarrow$ 2005: more failures at the central database.

Illustrative Detector Maps





Slanted streaks: at successive detectors at successive time periods.
Short horizontal lines: high occupancies during day-time.

Travel Time Estimation: Problem Description

We are interested in the computation of travel times, based on historical flow measurements*, obtained at both ends of a motorway section without on-/off ramps in between.

(⋆) For single inductive loop detectors, total vehicle counts are the most reliable.

Travel Time Estimation Algorithm

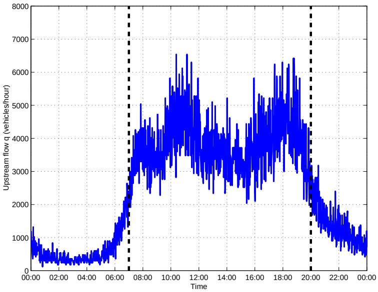
Assumptions

- There is conservation of the number of vehicles in the section.
- The *first-in, first-out* (FIFO) condition holds.

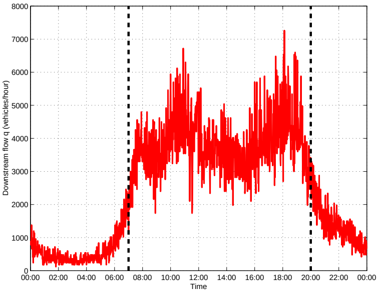
(1) Aggregate flow measurements over all lanes.
(2) Convert flow measurements into cumulative counts.
(3) Synchronise upstream and downstream cumulative curves.
(4) Correct for systematic errors between both posts.
(5) Extract the distribution of the dynamic travel time.

An Example for Travel Time Estimation on the E40

Consider the E40 motorway between Erpe-Mere and Wetteren (three lanes), on Monday, April 4, 2003.



Upstream flows



Downstream flows

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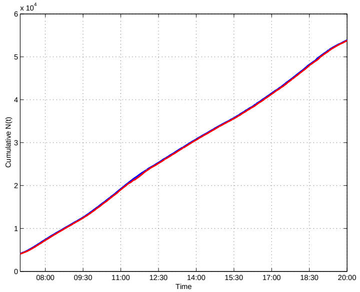
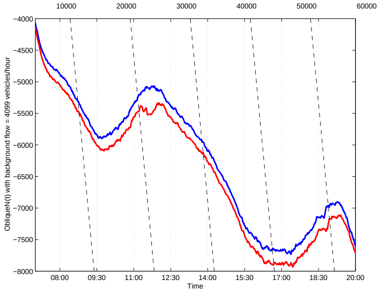


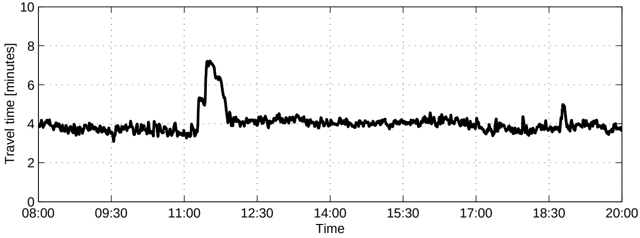
Cumulative curves

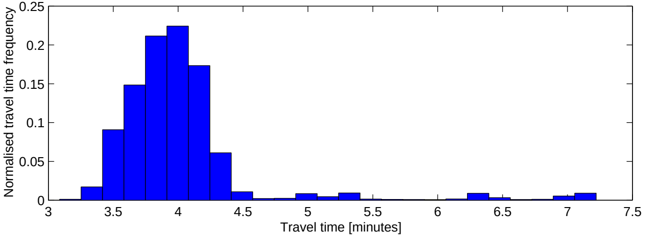


Oblique plot

⇒ There is a queue growing at approximately 11:00.

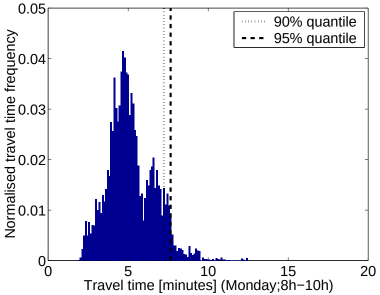
Extracting the Distribution of the Dynamic Travel Time

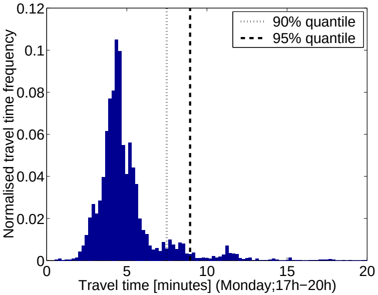




Assessing Travel Time Reliability

For a typical Monday in 2003, this becomes:





Median	=	5.16 minutes
MAD	=	0.43 minutes
90%	=	7.23 minutes
95%	=	7.66 minutes

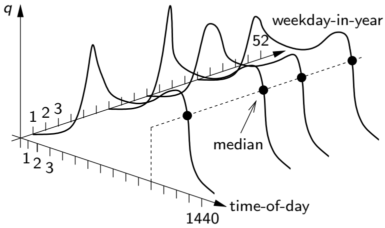
Median	=	4.97 minutes
MAD	=	0.45 minutes
90%	=	7.49 minutes
95%	=	8.95 minutes

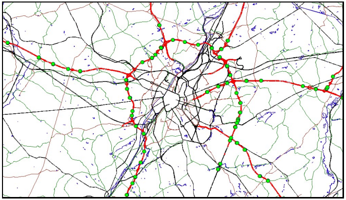
Constructing Tempo-Spatial Congestion Maps

For a given motorway, consider all measurements made on similar weekdays. Use the mean speed as an indicator for congestion.

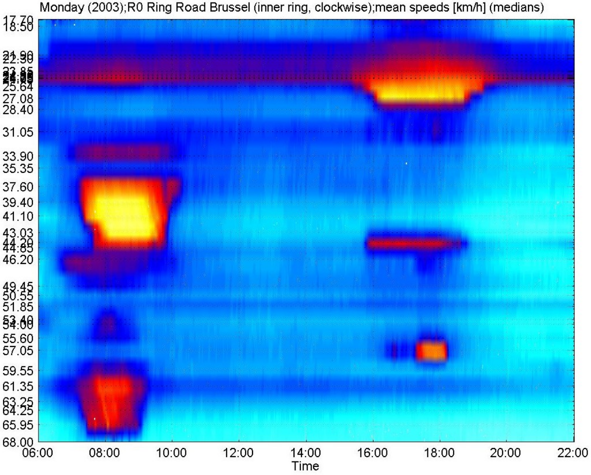
Robust estimators to eliminate outliers

The median (= 50% quantile) gives structural congestion.
The 95% quantile gives incidental congestion.





Structural Congestion on the R0 Ring Road



Monday

Severe morning congestion around Vilvoorde and Strombeek-Bever. Slower traffic at Machelen (E19) and Merchtem (E40).

Severe evening congestion around Vierarmenkruispunt, Tervuren, Wezembeek-Oppem.

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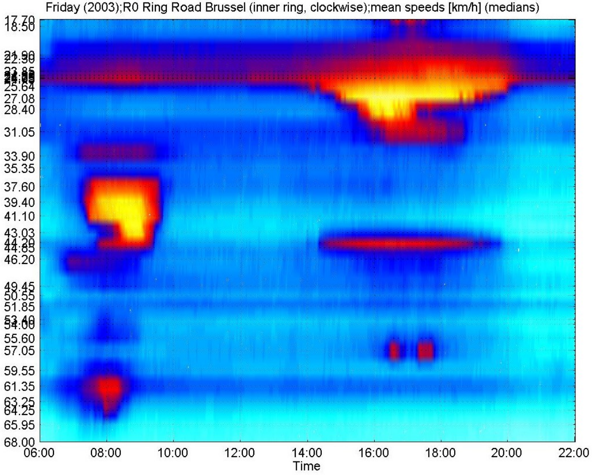


Friday

Typically a more pronounced evening congestion, as opposed to a milder morning congestion.

Longer evening rush hour, especially near Vierarmenkruispunt and Strombeek-Bever.

Part III

Integrated Dynamic Traffic Assignment

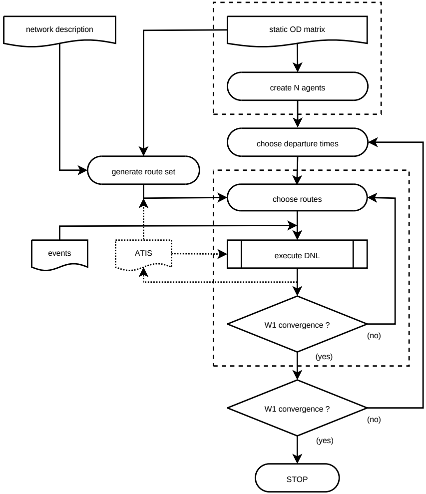
Approaches to Dynamic Traffic Assignment

It is important to capture the temporal character of congestion (i.e., its buildup and dissolution). Travel times depend on the history of the system, implying dynamic traffic assignment (DTA):

- Analytical versus simulation-based DTA.
- Deterministic versus stochastic DTA.
- The integration encompasses the following components:
  - Departure time choice (DTC).
  - Dynamic route choice (DRC).
  - Dynamic network loading (DNL).

⇒ Incorporate a given synthetic population.
⇒ Assume heterogeneous unimodal traffic, using an efficient DNL.
⇒ (DTC + DRC) + DNL ⇒ equilibrium.

Overview of the Proposed Framework



⇒ Sequential DTC + DRC

(1) Disaggregate static OD matrix into N agents.

(2) Generate set of feasible routes.

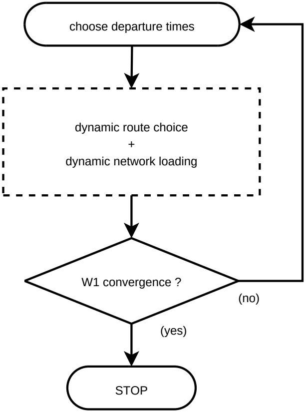
(3) Execute departure time choice (DTC) model.

(4) Execute dynamic route choice (DRC) model.

(5) Execute dynamic network loading (DNL) model.

(6) Check convergence.

Departure Time Choice



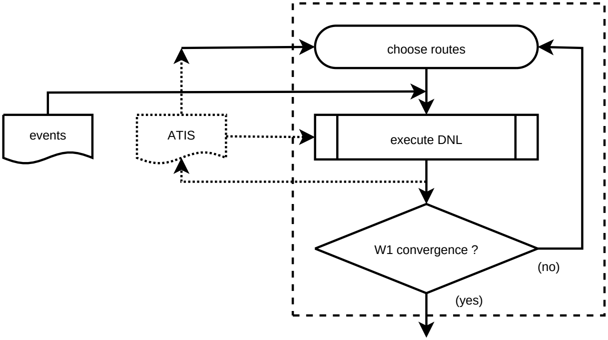
Check convergence using an agent's generalised travel cost:

$$
\begin{aligned}
C_{\text{total}_i}(t_{\text{departure}_i}) = \\
& C_{\mu_i}(\mu_i(t_{\text{departure}_i})) + \\
& C_{\text{T}_i}(T_i(t_{\text{departure}_i})) + \\
& \max\{C_{\beta_i}(t_{\text{PAT}_i} - \\
& \qquad (t_{\text{departure}_i} + T_i(t_{\text{departure}_i}))), 0\} + \\
& \max\{C_{\gamma_i}(t_{\text{departure}_i} + \\
& \qquad T_i(t_{\text{departure}_i}) - t_{\text{PAT}_i}), 0\}.
\end{aligned}
$$

$\Rightarrow$ Take schedule delay costs into account.

Dynamic Route Choice

Assuming known departure times, all agents now select a route from the set of feasible routes between their origins and destinations.



An Efficient Dynamic Network Loading Model

We adopt a microscopic simulation approach.
BUT: Car-following and lane-changing submodels typically entail a high-computational burden.

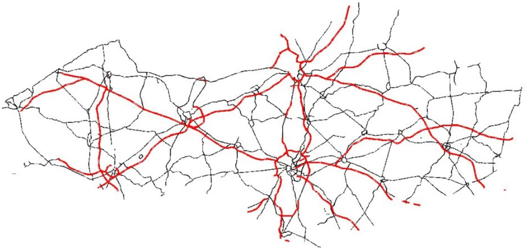
$\Downarrow$

Consider a traffic cellular automaton as the underlying DNL model:

- Site oriented versus particle oriented $\Rightarrow$ hybrid approach.
- Flexible architecture with respect to the choice of TCA model.
- Slowdown probabilities et cetera are properties of the links.
- Java$^{\text{TM}}$: performant and *"write once, run anywhere"*.

Tackling Large Scale Aspects

Even when using an efficient microscopic model like a traffic cellular automaton, large-scale scenarios provide a true challenge.

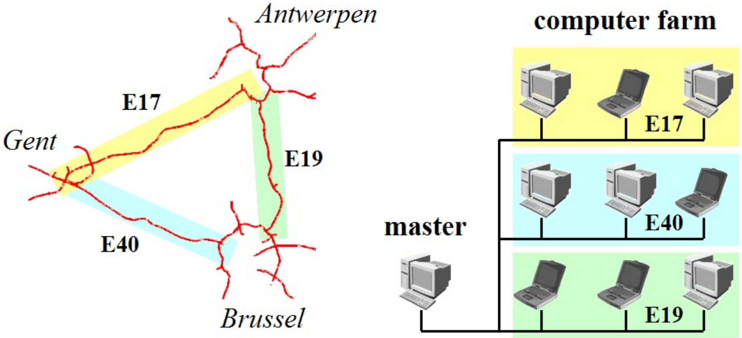


⇒ Flanders has ≈ 1300 km of highway roads.
⇒ This corresponds to ≈ 520,000 cells (7.5 m/cell; 3 lanes/road).

Solution: divide the workload over different workers.

Parallellism Through Distributed Computing

⇒ We assume deployment in a heterogeneous environment (mixing grid-based and high-performance computing). Assign all motorways to separate computing units:



Part IV

Summary and Perspectives

Summary and Contributions

- With respect to the state-of-the-art, we have provided:
  - A logical and consistent terminology and notation to tackle the existing a 'zoo of notations' (Chapter 2).
  - An extensive overview for traffic flow theory, transportation planning, and traffic flow modelling (Chapters 2 and 3).
  - A complete survey and classification of traffic cellular automata models from the behavioural point of view (Chapter 4).
- Considering traffic flow measurements, we have provided (Chapter 6):
  - A method to track statistical outliers.
  - A visual technique for quick assessments of structural and incidental detector malfunctioning.
  - A methodology for deriving travel times based on raw cumulative counts.
- Sequentially combining departure time choice and dynamic route choice, we propose a framework for dynamic traffic assignment, based on an efficient dynamic network loading model (Chapter 7).

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Future Research

- Considering the state-of-the-art:
  - A consequent analysis of the developed traffic flow models (mathematical properties, physical soundness, strengths and weaknesses).
  - The humanities and social sciences should consider the psychological aspects of human beings (e.g., self-organisation of the transportation system).
- Mining data stemming from detectors, GSM/GPS probe vehicles, ... to extract relevant and up-to-date traffic information (interaction between competitive producers and consumers).
- Construct a practical implementation of the proposed framework (considering calibration and validation issues, and the existence of an equilibrium).

Future Research

- Considering the state-of-the-art:
  - A consequent analysis of the developed traffic flow models (mathematical properties, physical soundness, strengths and weaknesses).
  - The humanities and social sciences should consider the psychological aspects of human beings (e.g., self-organisation of the transportation system).
- Mining data stemming from detectors, GSM/GPS probe vehicles, . . . to extract relevant and up-to-date traffic information (interaction between competitive producers and consumers).
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